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Experimental digital transmission of multiplexed video and audio signals at 60 M bit/s through a satellite

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Summary

In May 1976 experiments were carried out in which 60 Mbit/s signals, generated by equipment constructed in Research Department, were transmitted through the Indian Ocean Intelsat IV satellite from the UK Post Office earth station at Goonhilly Downs, Cornwall. An outline of the experimental equipment is given together with a description of the transmission tests. Several interesting facts which emerged are discussed, mainly concerning the need for scrambling and the error performance.

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1. Introduction

The use of digital techniques by the BBC for broadcast programme distribution from the studio centres to the transmitters in the UK is well-established for sound signals[1] but as yet video transmission is entirely analogue. Video signals are distributed nationally in analogue form via f.m. s.h.f. radio links and international exchange takes place via satellites, again using analogue f.m. techniques. When transmitted over long distances analogue signals are subject to cumulative degradations resulting from the effects of noise and distortion on the links over which they travel. The possibility of avoiding these impairments and/or reducing costs by using digital techniques for video transmission has accordingly been under consideration for some time.

A previous Report[2] describes experiments made by the BBC in conjunction with the UK Post Office (UK PO) which explored the possibilities of simultaneous sound and video transmission by digital means over a cable link. The link capacity was 120 Mbit/s and the BBC test signal comprised two interleaved 60 Mbit/s 'packages', each providing one video channel and six high-quality sound channels.

This Report describes experiments conducted in conjunction with the UK PO at the Goonhilly Downs Satellite Earth Station in which the feasibility of using digital transmission of video and sound signals over a satellite link was demonstrated. The transmitted bit rate was 60 Mbit/s, i.e. one 'package' as referred to above and the experiments are believed to be the first in which digitally-coded System I colour television signals have been conveyed by satellite. (An experimental system known as DITEC has been evolved by COMSAT for digital transmission of NTSC colour signals).[3]

Sections 2 to 4 of the Report describe the operational and experimental apparatus used in the tests while the tests themselves are described in Sections 5 and 6.

2. The satellite transmission system

There are three large (30 m) dish aerials in use at Goonhilly, each normally being dedicated to a particular Intelsat satellite. Two aerial systems are used in conjunction with satellites positioned over the Atlantic Ocean. The other, known as Aerial 1, is used with a satellite over the Indian Ocean; this was the combination made available for the tests. All three satellites are of the Intelsat IV type.

Signals are transmitted to the satellite in the 6 GHz band while 4 GHz is used from the satellite to the earth station. Frequency translation between the two bands is performed in the satellite by transponders. The band is divided into 12 adjacent 40 MHz segments, with a transponder for each. About 36 MHz of each 40 MHz segment is available for use, the remainder providing a guard space between segments in which interference monitoring may be performed.

Modulated signals are distributed about the earth station at a 70 MHz i.f. Up- and down-converters are used to translate the i.f. to 6 GHz for transmission and from 4 GHz to i.f. in reception. Travelling-wave-tube amplifiers amplify the up-converted signals at 6 GHz to feed the aerial; each such high-power amplifier (h.p.a.) simultaneously handles signals destined for several transponders. The signals from the satellite received by the aerial dish are amplified by a low-noise parametric amplifier prior to down-conversion.

For normal television transmission at the time of the experiments use was made of the whole 36 MHz capacity of one transponder.* The video signal was frequency-modulated onto a carrier which was offset from the transponder centre frequency by 3 MHz, the modulated signal having a bandwidth of 30 MHz. A 6 MHz 'slot' thus remained, in which audio signals for programme and cue purposes could be carried, also by frequency modulation. For Aerial 1 there is a h.p.a. devoted to television transmission; however, when it is not used for this it functions as a standby unit for the other amplifiers carrying telephony.

3. The BBC experimental 60 Mbit/s system

The BBC multiplex equipment was basically the same as that which was used for field trials of a Post Office 120 Mbit/s digital line system in 1975.[2] Minor alterations were made in order to operate at 60 Mbit/s and to provide signals conforming to an agreed interfacing standard.

The multiplex equipment[2] (Fig. 1) assembled a 60 Mbit/s 'package' which could carry one video signal and up to six high-quality sound signals; two of the sound channels were fully-equipped with coders and decoders. The equipment had originally interleaved two such 60 Mbit/s signals to produce a 120 Mbit/s signal; thus a single 60 Mbit/s signal could easily be obtained.

The System I PAL video signal was coded using a combination of sub-Nyquist sampling and differential pulse code modulation (d.p.c.m.) techniques.[4] The analogue signal was first passed through a comb filter, then sampled at twice subcarrier frequency ($2 f_{sc}$)* and quantised to 8-bit accuracy. The resulting 8-bit p.c.m. sample words were then reduced to 6- or 5-bit words in a d.p.c.m. coder. Optional 6- or 5-bit coding could be chosen by exchanging circuit boards. The 6-bit system offered a choice of conventional d.p.c.m. or hybrid p.c.m./d.p.c.m., second-previous sample (i.e. one subcarrier period) prediction being used. The 5-bit system used hybrid p.c.m./d.p.c.m. only but with the choice between second-previous sample prediction or an adaptive mode. The adaptive mode selected a prediction from the previous or second-previous sample according to the size of difference signal produced. It was also possible to send 6-bit p.c.m. without any differential coding – this was useful for investigating pattern-dependent effects.

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* Since the experiments were performed it has become normal practice to use one half of the transponder bandwidth for each television transmission, thereby gaining channel capacity at the expense of signal-to-noise ratio.

Since video signals which are coded with d.p.c.m. techniques are particularly vulnerable to the effects of transmission errors[5] an error-correction facility was provided. The d.p.c.m. signal, in parallel form, was passed through the error-correction coder before being multiplexed. The Wyner-Ash (16, 15) single-error-correcting convolutional code was used,[6] implemented in the form of six Wyner-Ash coders, each operating on one of the six parallel video streams. This arrangement has the advantage of offering a degree of burst-error protection to the signal when finally serialised, as well as reducing the speed of operation of the logic circuits and thus easing circuit design.

The sound signals were coded using a 'near-instantaneous' digital companding technique.[1] The signal is sampled at 32 kHz and quantised to 13-bit accuracy but is then described using only 10 bits per sample word; an accuracy corresponding to 13, 12, 11 or 10 bits resolution is chosen for each successive block of 32 words according to the peak amplitude occurring in that block. A 2048 kbit/s** signal is produced when six signals so coded are multiplexed. The design of the sound multiplex allows for error protection by parity checking and concealment of erroneous samples, but this facility was not available for the trials.

The video bit rate with 6-bit coding is 53·2 Mbit/s, which is increased to 56·75 Mbit/s by the error-correction coding. Adding this to the sound rate of 2048 kbit/s we obtain 58·8 Mbit/s. The gap between this and the 60 Mbit/s transmitted is filled with the bits used to control framing and justification in the multiplexing process. Justification is required since the input and output bit rates are unrelated and may vary independently within certain tolerances.[7]

Section 5 relates how preliminary tests suggested the need for scrambling. Provision was therefore made for scrambling to be available for the main trials. It was decided to use self-synchronising feedback scramblers in the parallel video signal *before* error-correction coding, with corresponding feed-forward de-scramblers in the receiver placed *after* the error-correction decoder. This arrangement meant that the operation of the error corrector was not upset by the inevitable error extension produced by this type of scrambler. A further discussion of scrambling is given in the Appendix.

The 60 Mbit/s output is obtained as two 30 Mbit/s streams by the arrangement shown in Fig. 2. In the original 120 Mbit/s system two 6-bit 10 Mword/s packages each had their own serialiser so that two 60 Mbit/s serial streams were produced, and, when the two were interleaved, an output at 120 Mbit/s was given. A minor modification involved taking only one 6-bit multiplex in 10 Mword/s parallel form and splitting it into two 3-bit 10 Mword/s signals, each being fed to a serialiser. Two outputs at 30 Mbit/s were thus obtained, with an interleaved 60 Mbit/s serial stream also available from the interleaver.

The receiving equipment was complementary to the sending equipment.

Facilities were provided for measuring the transmission path error rate while programme-type signals were being transmitted. Two methods could be used:

(i) monitoring the rate at which error correction of the video signal took place,
and (ii) monitoring the frame-alignment sequence at the demultiplexer.

In either case the error rate was computed and displayed in the form m errors in 10^n. As the frame-alignment sequence could be chosen at will, it was possible to use method (ii) as a means of investigating pattern-dependent effects. Methods (i) and (ii) will be referred to as VID and FAW monitoring modes respectively.

The two 30 Mbit/s streams (with clock) were fed to the Post Office system and two 30 Mbit/s streams received back again. The 60 Mbit/s single stream which was simultaneously available from the BBC sender was fed to the BBC receiver via a unit which could insert random errors at known rates. The BBC receiver could thus select two inputs:

(i) 2 x 30 Mbit/s, via the Post Office equipment,
or (ii) 60 Mbit/s, BBC digital system 'back-to-back' with random errors added.

It was thus possible to compare the effect of any errors caused in the Post Office equipment and satellite path with errors known to be random, at known rates.

4. The Post Office experimental modem

The function of this apparatus was to translate the 60 Mbit/s digital signal into a modulated carrier form

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* f_{sc} = 4·43361875 MHz for the 625-line PAL systems.

** 2048 kbit/s is the agreed bit rate for the first-order multiplex in the European digital network hierarchy.

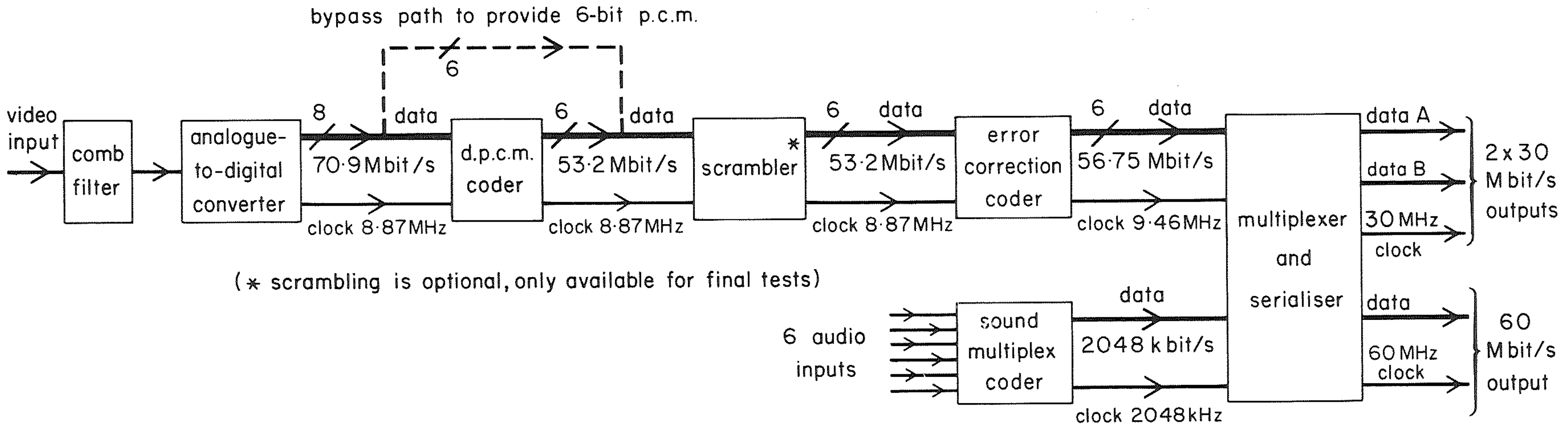

Fig. 1 - BBC 60 Mbit/s multiplex block diagram

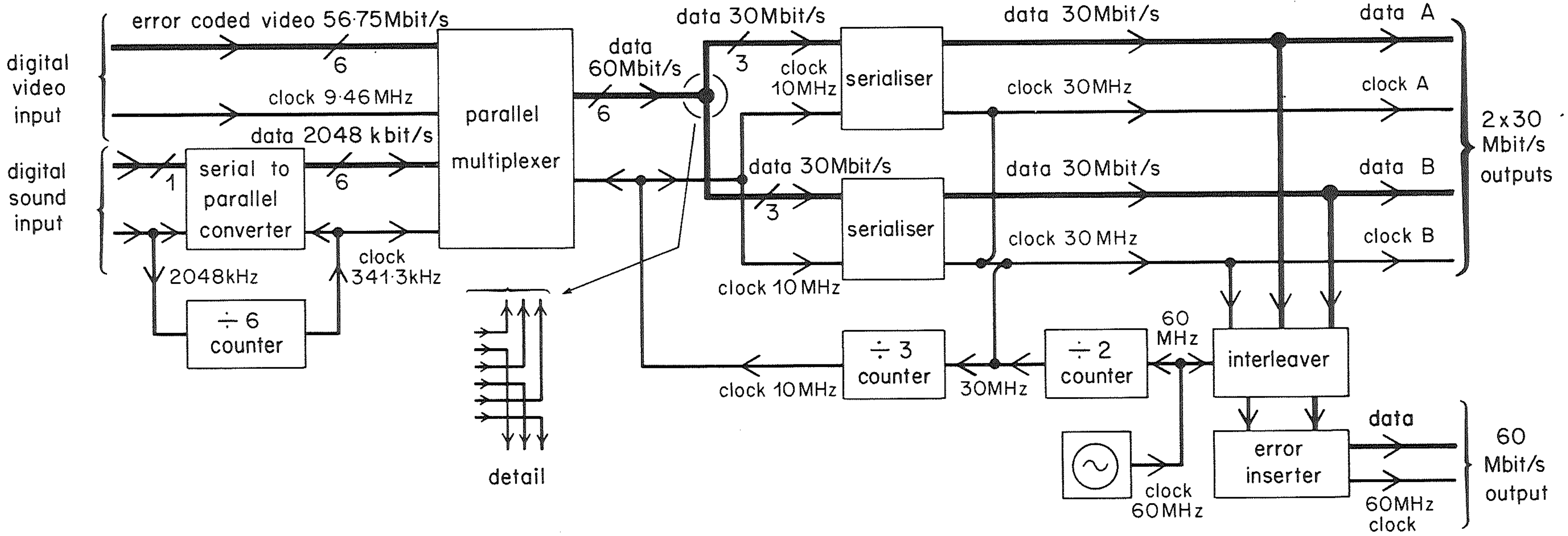

Fig. 2 - Arrangement providing 2 x 30 Mbit/s data format

occupying 36 MHz bandwidth, which could then be carried by one satellite transponder.

The form of coding and modulation used to perform this function is known as 4-phase differential-phase-shift-keying (d.p.s.k.).[8] The incoming bit stream is divided into symbols each containing two bits, so that the symbol rate is half the bit rate. Information is modulated onto a carrier by causing the carrier phase to take one of four values spaced 90° relative to a reference carrier. Each symbol contains two bits and thus has four possible states, so a simple coding system could relate each symbol state to a corresponding carrier phase. However, to demodulate a signal coded in this way, a reference carrier of known phase would be needed at the receiver. This is avoided by relating the four symbol states to the four possible *changes* of carrier phase between one symbol period and the next. A simple logic circuit is used in the modulator to determine which *absolute* carrier phase should be sent to produce the required phase *difference* between one symbol period and the previous one. This process is called differential encoding.

The Post Office experimental modem accepted a 60 Mbit/s digital input in the form of two streams at 30 Mbit/s with an accompanying clock signal at 30 MHz, i.e. the symbol rate. The demodulator output was in the same form. The information was modulated onto a 70 MHz carrier and bandlimited with a spectrum-shaping filter having a bandwidth of 36 MHz measured at the −15 dB points. The resulting signal was in a form which could be fed into the station i.f. distribution network for subsequent up-conversion and transmission to the satellite.

The modulation process described may be thought of as simultaneous amplitude modulation of in-phase and quadrature carrier components; if the two components are multiplied by ±1, four different resultant phases can be produced. This represents one possible modulator technique and also suggests how to demodulate. Two synchronous detectors are fed with the received signal and with reference carrier-frequency signals in quadrature. The two resulting demodulated waveforms are 'sliced' and sampled by the regenerated clock to produce two digital streams at symbol rate. These are processed by a simple logic circuit which reverses the differential encoding process to produce two bit-streams corresponding to the original inputs to the modulator.

Two further aspects of the demodulator are worthy of discussion — carrier recovery and clock regeneration. The demodulation process described above requires two quadrature components at carrier frequency to be available to feed the synchronous demodulators; a carrier frequency signal must therefore be locally generated in the receiver. The method used in the Post Office demodulator is to multiply the frequency of the received modulated 70 MHz i.f. signal by a factor of four using non-linear elements. The 280 MHz signal produced is passed through a narrow-band filter and then divided by four; the resulting 70 MHz signal could be in any of four possible phases but the differential decoding process following demodulation removes any ambiguity which would otherwise occur.

Clock regeneration is necessary so that a regular bit stream may be produced from the sliced outputs of the two synchronous demodulators. Two methods were available in the PO demodulator — burst-mode and phase-locked mode. The burst-mode method used a fast-acting circuit which is intended for use in T.D.M.A.* applications where short bursts of data are encountered. However, when some digital signals having too few data transitions are encountered this circuit fails (see Section 5). The phase-locked mode used a phase-locked oscillator with a low loop bandwidth fed from the burst-mode clock regeneration circuit. When burst-mode regeneration fails the phase-locked oscillator 'flywheels' until regeneration is re-established.

As it was an experimental arrangement, the PO demodulator was provided with means for monitoring and measuring signals at various points and with the facility to add noise to the input signal via a calibrated attenuator so that the performance at various known carrier-to-noise ratios could be investigated.

5. Preliminary tests

Preliminary tests took place at Goonhilly on the 27th and 28th April 1976, and were intended to clear away any major difficulties before the main tests. Clearly, it was desirable to ensure that all the ground equipment would perform satisfactorily before trying to use the satellite. The main point to check was that the 60 Mbit/s signal produced by the BBC equipment would pass through the Post Office d.p.s.k. modulator and demodulator without undue degradation. Further tests were a check of interfacing compatibility and the use of a ground station and/or satellite simulator in conjunction with the PO modem.

Certain simplifications were made to the BBC equipment for these preliminary tests so that heavy transport was unnecessary. Previous experience with digital line system experiments[2] and others had suggested that the digital video component of the 60 Mbit/s package would probably be the cause of any special effects that might appear when the BBC signal was passed through a transmission system instead of the pseudo-random binary sequences (p.r.b.s.) often used in testing. This is to be expected since the video signal occupies most of the package (56·75 Mbit/s out of 60) and is highly structured owing to the scanning format. Furthermore, it was expected that p.c.m. video would constitute a more stringent test than d.p.c.m. so far as picture-dependent effects were concerned. Thus the sound coding and decoding equipment was omitted for these tests, also the video d.p.c.m. coder and decoder, so that video was coded as 6-bit p.c.m. (Transmission errors are of course more visible with d.p.c.m. but for this test the error-monitoring facility incorporated in the BBC equipment would give information about the error rate anyway).

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* T.D.M.A. is an abbreviation for 'time-division multiple access' which refers to a digital transmission system in which, by means of reference timing signals, a number of earth stations share a common satellite transponder on a time-division multiplex basis.

Video signals were available from an off-air receiver or a BBC digital colour-bar generator which could produce several combinations of colours in horizontal or vertical bars, or in a chequerboard pattern.

The Post Office equipment comprised the d.p.s.k. modem, a ground-station simulator and a satellite simulator (see Fig. 3). The modem could be looped at 70 MHz i.f. in order to test its basic characteristics, or linked to either or both of the simulators via up- and down-converters. The ground station simulator used a high-power travelling-wave-tube (T.W.T.) amplifier with dummy load. The satellite simulator also used a T.W.T. amplifier, but of much lower power rating. Means were provided to add measured amounts of noise to the signal.

Interfacing tests proved entirely satisfactory.

Attempts to pass the BBC signal through the Post Office d.p.s.k. modem, looped at i.f., were at first unsuccessful. It was discovered that the clock regeneration circuit in use in the PO demodulator was intended for burst-mode operation (as would be used in a T.D.M.A. system). It could be expected that this circuit would fail to work properly, since data transitions in the BBC signals were insufficiently frequent. An alternative continuous-mode clock regeneration circuit using a phase-locked loop was therefore connected in.

A further difficulty was then revealed. Transmission of some pictures was satisfactory (e.g. 100% colour chequerboard) but many other pictures suffered localised very high error rates. A particular example was flesh-tones* in bar or chequerboard format in which two of the eight flesh-tones suffered a high error rate but the rest of the picture was satisfactory. The cause of this picture-dependent error generation was found to be failure of carrier recovery in the PO demodulator. (Carrier must be recovered before demodulation may take place).

The process of carrier recovery in a d.p.s.k. system with low relative bandwidth (in this case 36 MHz for 2 x 30 Mbit/s capacity) is not bit-sequence independent. When certain data sequences are transmitted there are no suitable carrier-related components of the signal available at the decoder from which the carrier may be extracted.[8] Thus either the carrier-recovery circuit must have a time constant which is sufficiently long to 'flywheel' through any periods when such sequences are transmitted, or it must be arranged that these sequences do not occur. Since the demodulator was also designed for T.D.M.A. operation the time constant was necessarily short.

Investigation of the spectrum of the modulated i.f. signal when those pictures giving difficulty were transmitted appeared to confirm that the cause of the problem was as described above. In view of the fact that television signals could give rise to awkward data sequences for relatively long periods of time, it was concluded that the only reliable solution would be to avoid transmitting such sequences at all. This meant that some form of scrambling would need to be applied.

No immediate solution was possible, so, in order to get further useful results in the time available, a 'cheat wire' feed of carrier was fitted between the modulator and demodulator. The bit-error rate (in the absence of added noise) was then zero for all pictures tried – both off-air and digitally generated. All subsequent tests in this visit used this 'cheat wire'.

A series of measurements of error rate (using the error-monitoring facilities in the BBC equipment) was then made for various values of carrier-to-noise ratio produced by adding noise into the i.f. part of the system. The results compared closely with those previously obtained by the PO using pseudo-random test signals; furthermore, the errors appeared to be randomly distributed on the monitor screen and the BBC Wyner-Ash error corrector made the expected improvements in picture quality.

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* A selection of colours provided by the colour-bar generator which are chosen to be representative of skin flesh-tones.

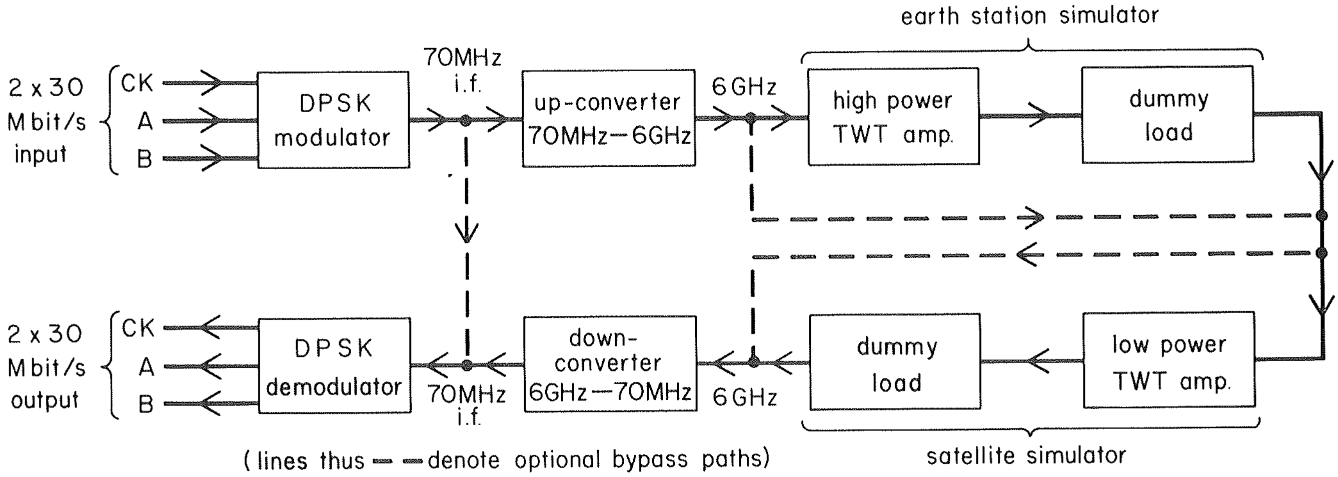

Fig. 3 - Post Office modulation and r.f. simulation equipment

The remainder of the preliminary tests was directed to using either or both of the simulators in the signal path. The operating points of the amplifiers in these simulators could be varied – this was of particular interest to the PO staff who wished to observe the effect on error rate of varying the non-linearity. It was therefore intended to repeat the error rate versus carrier-to-noise ratio measurements for various operating conditions.

In practice no really consistent results were obtained for the following reasons:

(a) When errors occurred, they tended to be 50 Hz mains-related, appearing as 'hum-bars' of errors. The reason for this was clear when the demodulated signal was observed on an oscilloscope – the eye height was modulated with a mains ripple. This was believed to be due to a power supply problem in the simulation equipment.

(b) The error rate was dependent on the picture in use although errors were all in mains-related 'hum-bars'.

(c) A general slow variation of performance with time seemed to take place. The cause was not located – it may have been drift in the operating point of the simulator amplifiers with temperature.

Error-free transmission was possible, however, and it appeared that any difficulties were caused by faults in the simulation equipment rather than by fundamental problems. The usefulness of a television display in revealing special characteristics of faults may be noted; the mains-related nature of the errors noted in (a) above was immediately obvious whereas using a pseudo-random binary sequence generator and associated error-measuring equipment it was merely known that the error rate was higher than might be expected.

The preliminary tests thus served their purpose in discovering an area of difficulty – carrier recovery failure – before the main tests which would use the satellite.

It was concluded that some form of scrambling would be required if failure of carrier recovery was to be avoided. It was possible that the use of d.p.c.m. coding in the main tests instead of p.c.m. would ease the problem, but this was uncertain. It was agreed that the PO would produce scramblers for use in the serial stream, and the BBC would produce scramblers operating in the parallel stream before and after the error-corrector coder and decoder respectively (see Appendix). The comparison of these two scrambling arrangements, using p.c.m. and d.p.c.m. video coding would form a useful part of the main tests.

6. Main tests

The main tests took place at Goonhilly from 16th May to 22nd May 1976.

6.1. Experimental arrangement

The complete experimental arrangement is depicted in Fig. 4.

Analogue video signals were transmitted between BBC Designs Department in London and Goonhilly via a Post Office s.h.f. two-way link. The signal sources available in London were a colour-slide scanner, a quadruplex video tape recorder and BBC TV network output. Various test signals were also available locally at Goonhilly.

Signals could be returned to London via the s.h.f. link and could be recorded there on video tape. The London–Goonhilly–London s.h.f. link produced no perceptible degradation of the video signal. Sound-in-syncs was used on the link to provide two-way voice communication between London and Goonhilly for the duration of the tests.

The sound signal sources available at Goonhilly were stereo programme from a tape recorder, a tone generator and an electronic gong.[9] Recordings of the audio output of the digital satellite link were made locally using a second tape recorder.

Switches were provided so that the BBC equipment could be used back-to-back or through the Post Office modem equipment. The Post Office equipment was also arranged so that the modem could be used back-to-back or through the satellite. It was also possible, by special arrangement, to compare the performance of the digital video signal through the satellite with that of an analogue f.m. video signal through the satellite, although this was not the main purpose of the tests.

6.2. Modem back-to-back

This Section discusses the tests in which the output of the Post Office modulator was connected to the input of the Post Office demodulator, without using the satellite link. The effect of the satellite link could be partly simulated by adding white noise at the input to the PO demodulator.

The purpose of these tests was to determine how well the modem performed, compared to theoretical predictions, when it was carrying pseudo-random binary sequences, digital video p.c.m. signals and digital video d.p.c.m. signals, for various carrier-to-noise ratios. Also under study was the effect of scrambling on p.c.m. and d.p.c.m. signals and the effect of the transmitted sequence on carrier recovery.

Two scramblers were tried; they were intended to aid carrier recovery by randomising the input to the modem and thereby more nearly assuring carrier-frequency-related components in the r.f. signal.

The BBC scrambler was effectively six scramblers in parallel, one inserted in each of the six parallel bit-streams

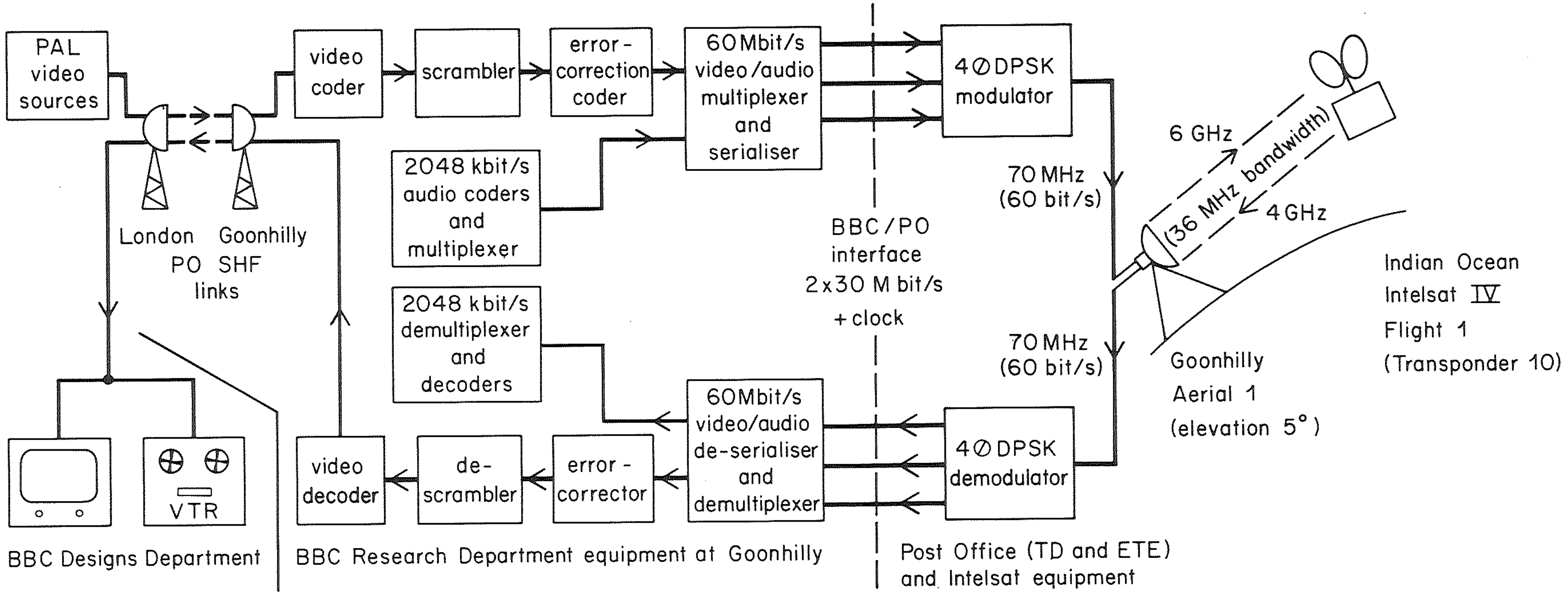

Fig. 4 - Overall experimental arrangement for 60 Mbit/s satellite transmission

at the input to the Wyner-Ash error-corrector coder. A complementary de-scrambler arrangement was used in the receiver at the output of the error corrector. This relative positioning of scrambler and error-correction processes was important. If the scrambler units had instead been inserted between the error-corrector coder and decoder then error-extension effects would have rendered the error corrector largely ineffective. This is because errors from the d.p.s.k. demodulator[8] can already span four bits and a further extension of, say, up to eight bits in the de-scrambler would have produced a total extension of burst of up to 12 bits. The error corrector, consisting of six interleaved separate correctors, as described previously could deal only with a burst of up to six bits.

Of course, with the arrangement actually used, any errors emerging from the error-corrector decoder were extended by the following de-scrambler but this was insignificant compared with the error propagation which occurred anyway in the subsequent d.p.c.m. decoder,[5] Scrambling and its application in the Goonhilly experiments is discussed more fully in the Appendix.

An alternative scrambler, provided by the Post Office, operated on the serial 30 Mbit/s outputs from the multiplexer. The de-scrambler had not been constructed, but by comparing the spectrum of the 70 MHz i.f. signal with and without the scrambler it could be seen that the spectral content of the output signal was far less dependent on the picture content when the scrambler was inserted.

The error rate was measured for various carrier-to-noise ratios when scrambled 6-bit d.p.c.m. was used. The results are plotted in Fig. 5 and are approximately 1 dB worse than those predicted by theory. Similar results were obtained by the Post Office using a p.r.b.s. signal.

6.3. Satellite tests

In order to test digital transmission through the satellite the PO d.p.s.k. modem was connected into the ground station 70 MHz i.f. system in place of the f.m. modem normally employed for television transmission. The f.m. video signal was of 30 MHz bandwidth, normally offset to one side of the available 36 MHz in order to leave space for a sound carrier which was derived in a separate modulator. It was therefore necessary to change various i.f. filters to suit the d.p.s.k. signal which occupied the full 36 MHz but could convey both video and sound information.

With video scrambling in use the bit-error rate (b.e.r.) obtained initially was in the region of 3 in 10^5. This was steadily improved by careful adjustment of i.f. group-delay equalisation. The equalisers already present were set for the original 30 MHz bandwidth filters and thus needed readjustment to suit the 36 MHz filters. In fact the arrangement of filters and equalisers which was available for the experiment was not ideal as it was not designed for the purpose; some compromise was thus involved.

When adjustment was concluded the PO measurement of b.e.r. using a pseudo-random sequence varied over the range 5 in 10^7 to 2 in 10^6. The carrier-to-noise ratio was measured as typically 16·7 dB.

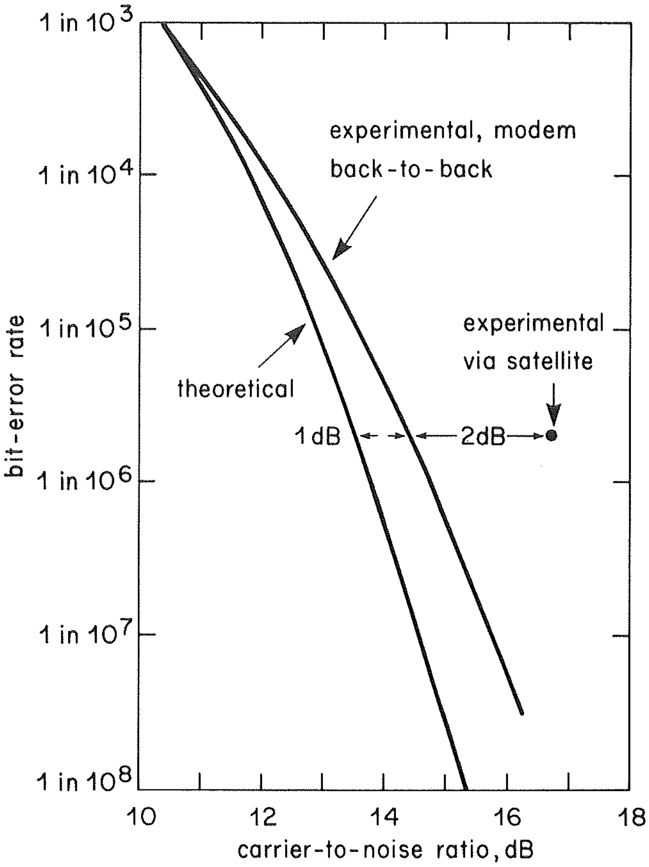

Fig. 5 - Error rate versus carrier-to-noise ratio

The measured b.e.r. using the BBC signal and monitoring facilities varied slightly depending on whether the PO clock recovery phase-locked loop was in circuit. For purely instrumental reasons, the precise phase of sampling the data "eye" could be adjusted more finely without the loop than when it was present. Thus the error rate was slightly higher when the loop was used, but this method of clock recovery afforded a greater resistance to the effects of slight changes in signal level which were found to occur from time to time.

Using "VID" monitoring mode (see Section 3), the error rate measured with the BBC signal was typically 2 in 10^6 using the phase-locked loop clock recovery circuit and a best figure of 6 in 10^7 was observed without it. These results are in good agreement with the PO results for pseudo-random test sequences. Furthermore, a subjective assessment of the picture quality with and without error correction showed that it was similar to that obtained when random errors of equal rate were added with the multiplexer and demultiplexer connected back-to-back. This suggested that the errors were occurring essentially randomly as single or short* burst errors.

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* "Short" here means "of burst length not exceeding six bits" — such burst errors are catered for in the BBC equipment by the interleaving of six Wyner-Ash error-correcting codes.[6]

Comparing these results with those obtained using the PO modem back-to-back (Section 6.2.) it may be seen that a degradation of performance roughly equivalent to a 2 dB loss of carrier-to-noise ratio occurred. This was presumed to be due to a combination of:

(i) the effect of the non-linearity of the TWT amplifiers used in the ground station and satellite power amplifiers (it should be noted that the ground station power amplifier was being operated at about 3 dB higher power than normal; this resulted in a satellite power output about 1 to 1·5 dB higher than normal – thus the satellite TWT was at saturation);

and (ii) distortion of the data eye caused by non-uniformity of group delay. This kind of distortion will cause crosstalk between adjacent symbols, usually referred to as intersymbol interference (ISI).

An increase in error rate due to effect (ii) should be pattern-dependent. For example, a single 1 in the middle of a stream of 0's might be decoded as a 0. On the other hand, intersymbol interference cannot have any effect on a long series of all 0's or all 1's. It was decided to investigate this using the FAW monitoring mode (see Section 3) in conjunction with the facility for varying the frame-alignment words of the BBC equipment. The FAW's corresponding to demodulated streams (a) all 0's (least susceptible to ISI) and (b) 010101 . . . (most susceptible to ISI) were evaluated taking into account the d.p.s.k. coding rules. These FAW's were tried in turn but because frame synchronisation was not then reliable each FAW was slightly modified by changing 2 of the 12 bits in the sequence. Synchronisation was then achieved and the error rates measured for the two conditions. The results showed some variation but the trend was consistently clear: situation (a) produced lower error rates than (b). Typically when VID monitoring* indicated 1 error in 10^6, FAW monitoring registered about 1 in 10^6 for (a) compared with 2 in 10^5 for (b) thus tending to confirm that ISI was present.

Under the conditions finally attained (carrier-to-noise ratio 16·7 dB, error rate $\approx$ 2 in 10^6) picture quality was virtually identical to that obtained using the BBC equipment back-to-back (with no bit-errors added) since the video error-correction is almost totally effective at this error rate.[2] The limiting factor determining picture quality was thus the basic video-coding system, in this case 6-bit h.d.p.c.m. with $2 f_{sc}$ sampling. This system had previously been assessed in formal subjective tests.[4]

An informal comparison of digital transmission with the present analogue f.m. technique was made. Because a quick changeover from one modem to the other could not easily be done, the direct comparison actually made was of f.m. transmission through the satellite with the BBC digital system back-to-back, but with errors added at the pessimistic rate of 1 in 10^5. The latter was a fair simulation since the only significant effect observed due to the digital *transmission* path was the introduction of bit errors. The impairments introduced by digital *coding* were a slight loss of high-frequency diagonal luminance resolution and also of vertical chrominance resolution, both resulting from the sub-Nyquist sampling technique, and "edge-busyness" introduced by the differential p.c.m. coding. The effect of transmission errors at the 1 in 10^5 error rate was found to be insignificant provided that error correction was in use. The main impairment resulting from the f.m. transmission system was the introduction of chrominance noise. The subjective comparison effectively resolved into the choice between two different types of impairment; diagonal luminance resolution loss versus chrominance noise, any other impairments of either system appearing relatively insignificant.

Those viewing the two systems in this comparison expressed a preference for the digital system, but it must be remembered that the comparison was not made under ideal viewing conditions and no attempt was made to conduct proper subjective tests. Furthermore, the f.m. system was not operating under its usual conditions, differing from normal in the following ways:

(i) the ground and satellite TWT's were operating at higher power than normal, with the satellite TWT at saturation (see above);

(ii) the vision carrier frequency was in the middle of the 36 MHz transponder bandwidth, whereas it is normally offset;

and (iii) the normal filters were not in use, and group delay equalisation of those in use was imperfect.

Point (i) would be expected to improve the video signal-to-noise ratio slightly whereas (ii) and (iii) could introduce some non-linear distortion.

Limited testing of the digital sound transmission apparatus was also performed. Unfortunately, the digital sound multiplex equipment used did not include any error protection, although this facility is allowed for in the design. The sound channel performance was therefore chiefly determined by the degree of impairment in the form of clicks introduced by the prevailing error rate. The bandwidth and signal-to-noise ratio (excluding error clicks) are of course determined by the coding system employed,[1] in the same way as for video.

Advantage was taken of the delay of the satellite path to perform a novel experiment. If the two audio channels available were placed in cascade, connecting the analogue audio output of one to the input of the other, the total delay was about half a second. A switch was placed at the input which selected either the output of a microphone amplifier or the output of the two transmission channels in cascade. It was then possible to "trap" a couple of words of speech in the loop so formed, producing a series of echoes. The point of interest in this was that each echo heard corresponded to the passage of the signal through two codecs; it was therefore possible to hear the effect of a very large numbers of codecs progressively in cascade. The signal was still perfectly intelligible after more than 50 coding and decoding operations, although the quality had, of course, greatly deteriorated by then.

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* Assumed to be accurate as an average indication since it monitors the majority of the multiplex signal – 56·75 Mbit/s out of 60.

No difficulties were encountered due to jitter, which was believed to be very small. Accurate measurements were not easily possible because the delay of the path via the satellite was not exactly constant but varied slowly and steadily due to the slight motion of the satellite relative to the earth. (Although nominally geostationary, some movement takes place about a fixed average position relative to the earth). The usual method of observing received clock pulses relative to transmitted clock pulses could not therefore be applied. The effect of satellite drift could be observed on a vectorscope which displayed the received video chrominance signal on a time-base locked to the transmitted video signal. The pattern of vectors displayed was observed to rotate at a rate proportional to the rate of change of path length, indicating a Doppler shift of subcarrier frequency. Typically, one whole cycle of rotation of the vector display was observed in about 20 seconds, i.e. a Doppler shift of 0·05 Hz in the subcarrier frequency (well within the PAL tolerance specification); this corresponds to a velocity component along the line joining the satellite and the ground station of about 1·5 m/s.

7. Discussion of results

From the broadcaster's viewpoint the results of the trials may be considered under the following headings:

(i) The performance limitations inherent in the digital *source*-coding schemes used. These may be assessed independently in the laboratory without any reference to a transmission system, and were determined at the outset when choosing what source-coding schemes should be used for the sound and vision signals in the experiment.[1,4]

(ii) The performance of the modulation system, i.e. the PO d.p.s.k. modem, as a means of *transmission* coding which carries a digital signal of a specified bit rate (60 Mbit/s) within a channel of defined bandwidth (36 MHz). A major aspect is the relationship between channel signal-to-noise ratio and bit-error rate, and any special effects dependent on the pattern of digits present in any particular message.

(iii) The performance of the PO modem and satellite path, as a digital 60 Mbit/s transmission channel which may be characterised by its b.e.r., jitter and any pattern-dependent effects.

(iv) The performance of the entire source coding and digital transmission system as a means of transmitting the television video and sound signals, compared with the conventional wholly-analogue transmission system.

The source-coding schemes have already been assessed. Reference 4 describes subjective tests which give an impairment grade on the EBU six-point scale of 1·97* for video 6-bit d.p.c.m. coding with sampling at 2 f_{sc}. This corresponds to a 'just perceptible' impairment. Reference 1 shows that for the sound signal no significant impairment is introduced by the use of near-instantaneous companding, compared with linear 13-bit p.c.m. coding which is accepted as adequate for broadcasting purposes.

The back-to-back tests of the PO modem showed that it performed close to the theoretical ideal for d.p.s.k. coding when carrying pseudo-random test sequences. The b.e.r. versus carrier-to-noise ratio characteristic roughly follows the theoretically-predicted shape but with a performance equivalent to a loss of about 1 dB in carrier-to-noise ratio. The performance is determined by the degradation of the data eye caused by the filters used for spectrum shaping and by imperfections in carrier and clock recovery.

When digital television signals were passed through the PO modem it was demonstrated that the performance of the modem was signal-dependent, some signals causing a complete failure of carrier recovery. Any link using such a modem is therefore not bit-sequence independent and some tailoring of the signals which are to be carried must be accepted. The use of scrambling was found to be sufficient to make the modem function equally as well with digital television signals as with pseudo-random test sequences. Scramblers bring problems of error extension but the configuration adopted with the BBC scramblers avoided any major difficulties. There may however be difficulties in a future operational digital transmission system if it is thought necessary to have scramblers permanently in circuit. It might not be practicable in such conditions to use the configuration used for the experiment without sacrificing the flexibility of a digital link, in particular the complete exchangeability of different digital signals of equal bit rate.

Further aspects of the system performance emerged when digital signals were conveyed over the satellite using the PO modem. Both pseudo-random test sequences and the digital television signal gave similar results for the average bit-error rate which was higher than was obtained using the modem back-to-back at the same signal-to-noise ratio. This suggested that an additional mechanism for producing errors, other than thermal noise, was present when using the satellite link. By monitoring the frame-alignment words of the digital television signal it was possible to show that some sequences were more susceptible to errors than others. This implies intersymbol interference was present and suggests that the performance of the channel filters was not ideal, especially with regard to group-delay variation. The filters used for the experiment were not designed specifically for the task so it is possible that a small improvement in performance could have been obtained if purpose-designed filters were used. The time delay through the link was found to vary as the satellite move slightly with respect to a truly geostationary position. This meant that accurate timing jitter measurements were not possible; however, jitter appeared to be very low in amplitude and no problems were caused by it.

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* This corresponds to grade 4·2 on the CCIR 5-point scale.

In summary, viewing the satellite chain and PO modem as a *digital link* we may say that it was not bit-sequence independent in two ways:

(i) scrambling was necessary with digital television signals if carrier recovery was to be guaranteed,

and (ii) the error probability was slightly higher for some bit-patterns than others due to intersymbol interference. However, the latter effect may well be a result of using filters which were to hand rather than specially-designed ones.

Jitter did not appear to be of any significance and the bit-error rate was of the order of 2 in 10^6.

Finally, we pass to consideration of the combination of digital-source coding, transmission coding and the satellite link as a means of conveying television signals to be compared with the normal analogue methods. Economy dictates that the satellite link is limited in bandwidth and signal-to-noise ratio so that either method of transmission must introduce some kind of impairment. In fact, the two methods introduce impairments which are different in character and also exhibit differences in the way in which they vary as a function of the carrier-to-noise ratio.

The main impairment with f.m. transmission is noise which is visible chiefly in highly-saturated coloured areas of the picture. The amount of noise visible will depend on the carrier-to-noise ratio, increasing with decreasing carrier-to-noise ratio until a point is reached where demodulation will fail. Under the prevailing conditions for the experiment some noise was visible; had the carrier-to-noise ratio varied there would have been a corresponding variation in the visibility of the noise.

The impairments introduced by the digital system fall into two classes, those due to source coding and those due to the effects of transmission errors. Variations in the carrier-to-noise ratio will only affect the latter. The source coding impairments are fixed and are relatively small, as discussed previously. At the prevailing carrier-to-noise ratio the error rate was such that no perceptible impairment resulted from transmission errors provided that the error corrector was in use. Thus if the carrier-to-noise ratio had improved there would have been no change in the received picture quality; if it had worsened *slightly* the picture quality would still be unchanged (the error corrector gives satisfactory quality up to an error rate of 1 in 10^5),[2] but beyond that any worsening of carrier-to-noise ratio would have produced visible effects due to errors and ultimately pictures would be unusable. The failure threshold is believed to occur at a carrier-to-noise ratio about 3 dB higher than for the analogue f.m. system.

Thus in the limit the f.m. system is more rugged than the digital system – pictures of some kind can be obtained at a lower carrier-to-noise ratio than for the digital system. At very good carrier-to-noise ratios the f.m. system is perhaps also superior to the digital system since the latter always has the basic, albeit small, impairment due to source coding. However, in the range of carrier-to-noise ratio around that observed in the experiments the choice is not so clear-cut. If the carrier-to-noise ratio were never significantly worse than the value observed the digital system would probably be preferred for its freedom from the visible effects of noise. However, if it is likely that the carrier-to-noise ratio could worsen significantly, then the f.m. system is preferable since under more extreme conditions a 'noisy' picture is probably better than one which is grossly corrupted by transmission errors, or even totally lost.

Comparison of the relative merits of the f.m. and digital modulation systems which can be used for satellite transmission of video signals was considered sufficiently important to merit further investigation. Tests were therefore made subsequently in the laboratory under controlled conditions so as to assess the differences more precisely.

The aim was to compare the picture quality for f.m. and digital modulation at various carrier-to-noise ratios. As neither of the Goonhilly modems was available the following methods were used to produce the pictures to be assessed:

(a) for *f.m.* a conventional f.m. modem was set to operate with the appropriate modulation characteristics and noise of appropriate bandwidth was added to give the desired carrier-to-noise ratios at the input to the demodulator;

(b) for *digital modulation* the BBC digital equipment was operated back-to-back with random errors inserted at rates equal to those measured at Goonhilly with the PO modem back-to-back at the desired carrier-to-noise ratios.

Note that in both cases it was the modem back-to-back performance which was replicated, representing the likely best performance that might be obtained in a practical transmission link using either type of modulation.

The tests were carried out under the viewing conditions specified in CCIR Recommendation 500. Television pictures were generated in a flying-spot slide scanner and fed to the two systems. Twelve observers were asked to compare pairs of pictures using the 7-point comparison scale, each picture pair presenting the results of f.m. and digital modulation for a particular carrier-to-noise ratio.

The results are plotted in Fig. 6, along with some relevant objective measurements. Similar curves would have resulted had these tests been made using real transmissions from Goonhilly over the satellite; instrumental deficiencies would have produced small changes, but from observations made at Goonhilly it is believed that the operating point was within the region defined by

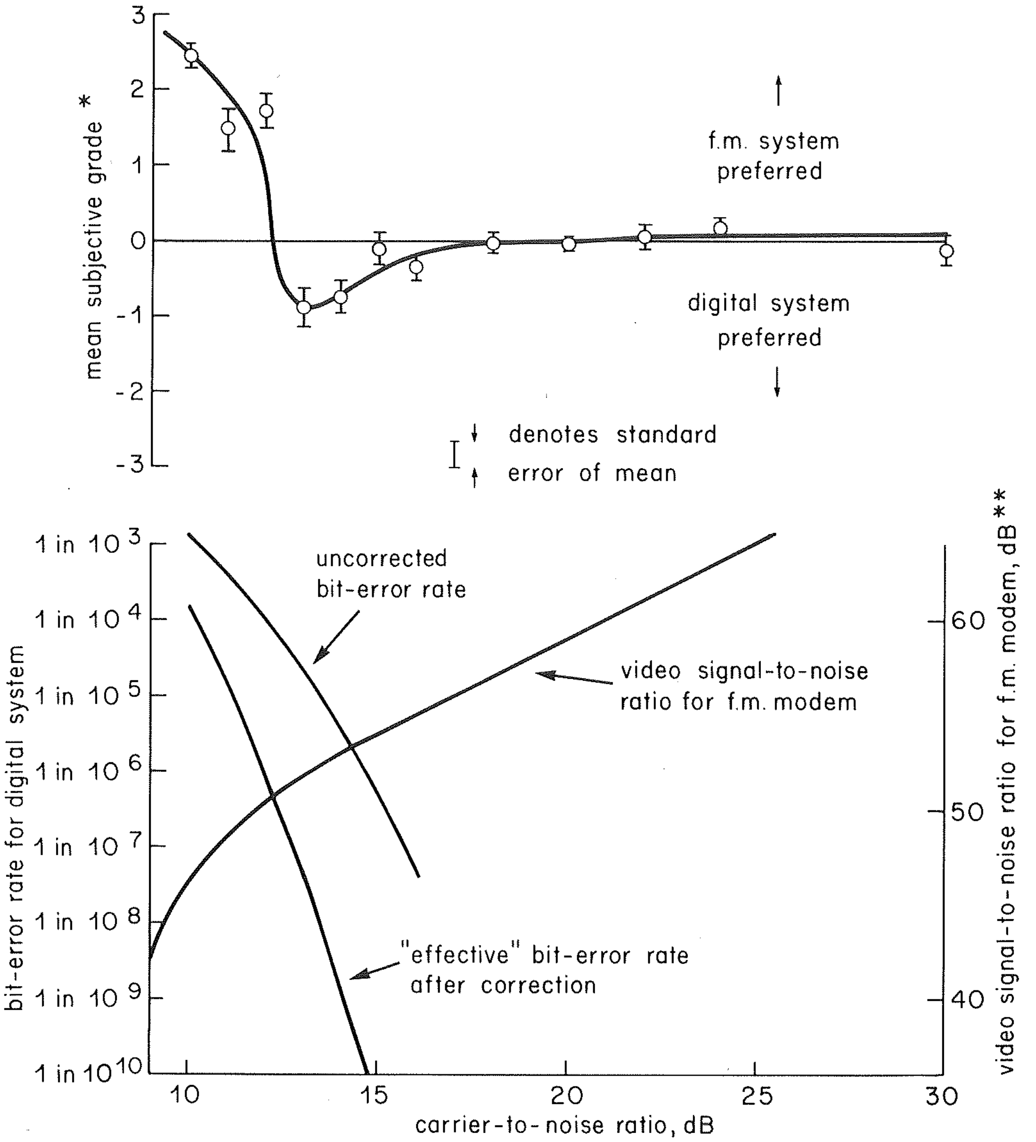

Fig. 6 - Comparative performance of the f.m. and digital video modulation systems determined by laboratory tests

* CCIR Recommendation 500 7-point comparison scale

** As defined in CCIR Recommendation 421-3 using systems BCGHF weighting network

the negative lobe of the comparison curve. The general shape of the comparison curve could be expected from the foregoing discussion, but note that the preference shown for digital modulation is small and only applies for a small range of carrier-to-noise ratio. It therefore appears that on performance grounds there is not a lot to choose between the systems unless very poor carrier-to-noise ratios occur, in which case f.m. is superior. The choice must be made on grounds of cost and convenience (e.g. flexibility of multiplexing).

It should be emphasised that Fig. 6 applies only to the parameter values appropriate to the Goonhilly exercise. Other values would produce different results, but the general form of Fig. 6 is still likely to occur.

The discussion has centred on the video signal since most experimental effort was devoted to it, furthermore the advantages of digital sound transmission are already well established.

8. Conclusions

In a joint BBC/PO experiment multiplexed video and audio signals have been successfully transmitted at a bit rate of 60 Mbit/s through a full-band transponder in an Intelsat IV satellite.

The trials emphasised the value of tests with real signals, i.e. signals representative of the form that digital video and digital sound for broadcasting may take, rather than tests with pseudo-random sequences.

It was found that, unless scrambling was employed, certain video signals could cause difficulties in carrier recovery and clock-pulse regeneration with the particular modulation system used. These difficulties arose mainly because the relevant circuits within the demodulator were designed primarily for the 'burst-mode' signals of TDMA digital telephony rather than for the continuously transmitted video/audio signals. The problems might be overcome by employing alternative circuits but it is nevertheless considered that scrambling is a preferred solution because of the more favourable r.f. spectrum which results.

Under the actual conditions of the field trial informal tests showed that the picture quality for digital transmission through the satellite was slightly better than that for f.m. transmission. Subsequent laboratory tests confirmed that digital transmission gives slightly better picture quality over a small range of carrier-to-noise ratio but that f.m. transmission is superior at very poor carrier-to-noise ratios.

Unless very poor carrier-to-noise ratios must be catered for it seems that the choice between the two systems must therefore be based on factors such as relative costs and operational convenience. In considering this it should be noted that digital transmission offers the superior efficiency and flexibility of time-division multiplexing.

It must be emphasised that the tests described were through a full-band (36 MHz) Intelsat satellite transponder. Further work would be necessary to decide the relative merits of f.m. and digital transmission with bandwidths other than 36 MHz.

9. Acknowledgements

The authors wish to acknowledge the valuable contributions to the experimental work described in this Report made by a large number of colleagues in BBC Research, Designs and Communications Departments, in the Telecommunications Development and Service Departments and External Telecommunications Executive of the UK Post Office. The co-operation of the authorities responsible for Intelsat operations in providing free use of the satellite channels for the experiments is also greatly appreciated.

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11. APPENDIX

Scrambling

11.1. The need for scrambling

An ideal digital transmission system would be able to accept any sequence of digits at its input and reproduce it exactly at its output, the sole effect on the sequence being to introduce a fixed time delay. In practice the sequence may be reproduced inaccurately, that is to say it may contain *transmission errors*, and the delay through the system may fluctuate, giving rise to timing *jitter*. If these effects occur randomly and independently of the actual sequence being transmitted, the system is said to be *bit-sequence independent*.* However, in practice this may not be the case, it being found that the occurrence of errors and jitter depends on the pattern of digits making up the transmitted sequence.

To give a simple example, suppose that NRZ binary signalling is used. If the transmitted sequence contains long sequences of all 1's or all 0's the receiver will be unable to regenerate clock pulses from the received sequence and errors will occur.

A similar problem could occur in the PO modem used for the satellite experiments and the phase-locked mode of clock regeneration was therefore necessary. Of greater importance, however, was the failure of carrier recovery when the digital television signals were passed through the modem. The failure mechanism here is more complicated; it arises because of the low relative bandwidth used for the d.p.s.k. signal. If the ratio of total signal bandwidth to symbol rate is less than 1·5, carrier recovery becomes impossible for certain digit sequences – see the discussion in Ref. 8, for example. The Goonhilly experiments fall into this category since the bandwidth/symbol rate ratio is 36/30 – 1·2.

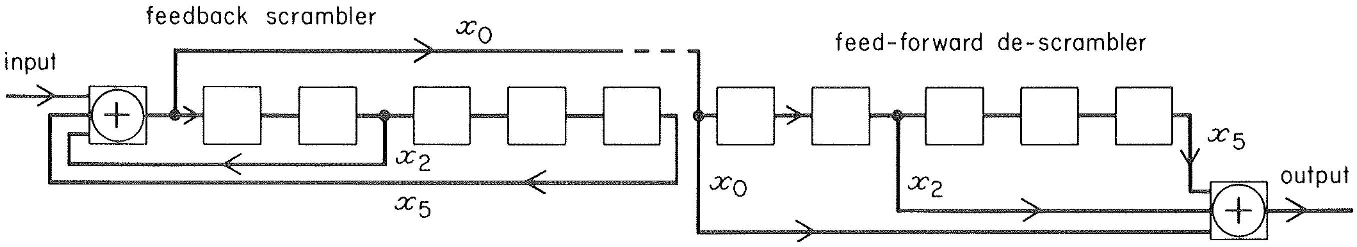
Scrambling is a technique which can be used to reduce pattern-dependency such as we have described. The basic idea of scrambling is to reduce the probability of failure of the transmission system by modifying the transmitted sequence in such a way as to reduce the probability of occurrence of particular sequences which would cause difficulty.

11.2. The self-synchronising scrambler

The self-synchronising scrambler[10,11] is a commonly-used configuration. The scrambler comprises a feedback shift-register circuit; the signal is fed into a shift register via a modulo–2 adder which has taps along the register as its other inputs (see Fig. 7). The de-scrambler is a complementary feed-forward arrangement; the signal feeds a shift register directly and the output is taken from a modulo–2 adder which adds the signals appearing at the input and at the taps. The Figure shows that the de-scrambler output will equal the scrambler input when the taps are at corresponding places in both.

The advantage of this type of scrambler is that it is self-synchronising, i.e. no extra synchronising signal is needed. The main disadvantage is that it causes error extension. If a bit is caused to be in error during transmission the resulting de-scrambled output will contain additional errors, one for each tap used on the shift register. Suppose the register is x elements long and has y taps (including the input tap). The effect of the de-scrambler is to increase the error rate by a factor of about y and to extend the length of any error bursts by x bits.

Clearly, we must choose the tap positions with care. To minimise possible problems caused by error extension both x and y should be kept small. However,



x_0 = input $\oplus\, x_2 \oplus x_5$

→☐→ denotes one clock period delay

$\oplus$ denotes modulo-2 addition

output = $x_0 \oplus x_2 \oplus x_5$

output = input $\oplus\, x_2 \oplus x_5 \oplus x_2 \oplus x_5$

output = input (since $a \oplus a = 0$)

Fig. 7 - Illustration of scrambling

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* The CCITT definition of bit-sequence independence, given in Recommendation G702 is: a digital path or digital section is bit-sequence independent at its specified bit rate when its design objectives permit any sequence of bits at that rate, or their equivalent, to be transmitted.

this will have an effect on the efficacy of scrambling. The usual requirement is for a scrambler to convert input sequences having a short repetition period into sequences having a long period which more nearly resemble a random signal. Reference 10 discusses the theory of the operation of self-synchronising scramblers and shows how the output period may be predicted for a particular sequence input to a particular scrambler. The general case is rather complicated so for brevity we shall list only the results for a simple case. If the input is all 0's the output generated is a pseudo-random sequence.[10] If the appropriate tap positions are chosen the sequence is a maximum-length pseudo-random sequence with a period of $2^x - 1$ bit periods (x is the number of elements in the shift register, as defined above). The table lists the tap positions for maximum length sequences for some values of x.

It may be seen that most of the cases listed have two taps in addition to the input so that y becomes 3. The case of x = 8 is unfortunate in that y = 5 so that error multiplication would be worse for the corresponding 8-stage scrambler than for those with the other lengths shown.

The output sequence length may fall below the maximum length of $2^x - 1$ when arbitrary sequences are presented at the scrambler input. It is clear that this must happen since no redundancy is added by the scrambler; the number of different sequences possible at the input and output is the same. The scrambler merely "maps" one sequence into another; if sequences with undesirable properties are converted into acceptable ones there must be some sequences which would have been acceptable which are made unacceptable. The usefulness of a scrambler must therefore be assessed statistically – scrambling will be beneficial if frequently-occurring undesirable sequences are improved at the expense of other sequences which occur only rarely.

11.3. Scrambling as applied in the experiments

As mentioned in Section 3, the scrambler and de-scrambler in the BBC equipment were placed so that the error extension of the de-scrambler did not disturb the operation of the error corrector. Thus, in the sending equipment, the scrambler was placed in the parallel stream between the d.p.c.m. coder and the error-corrector coder, with a corresponding placing of the de-scrambler in the receiving equipment. The signals at these points were in 6-bit parallel form so 6 identical scramblers and de-scramblers were provided, one for each bit stream.

Each scrambler had an 8-stage shift register with a flexible arrangement for selecting tap positions. Any self-synchronising scrambler – maximum length or not – which had 8 or less shift register stages could be realised. Each of the 6 parallel scramblers could have its format so varied independently of the others.

11.4. The effect of scrambling in the experiments

The preliminary tests (see Section 5) indicated that carrier recovery could not be reliably obtained when p.c.m. video signals were passed through the modem without scrambling. The main tests confirmed this, but with the d.p.c.m. signals that were then also available the problem was much reduced. The introduction of scrambling with d.p.c.m. did then reduce the error rate slightly so as to equal that obtained using pseudo-random test sequences.

As the p.c.m. signals proved to be a more stringent test than d.p.c.m. signals, some experiments were made using p.c.m. in order to assess the effect of varying the scrambler length. At first the 6 parallel scramblers were changed together in step from length 2 stages upwards. A steady improvement was obtained as the length was increased until satisfactory results were obtained with 5 stages. No further improvement was then apparent for 6, 7 or 8 stages. Another test was performed in which the parallel scramblers were set to different lengths or taken out of circuit in turn. This showed that reliable results were only obtained when all 6 scramblers were in operation.

Observation confirmed that the modulated signal spectrum was made more uniform by the use of scrambling, showing in another way that the necessary components for carrier recovery were made available. These observations demonstrate another advantage of scrambling. In the satellite transmission system the band-limited modulated signal subsequently passes through amplifiers which may be non-linear so that out-of-band intermodulation products may result. These products may cause adjacent-

Tap positions for maximum length pseudo-random sequence generation

x (shift register length in bits)	$2^x - 1$ (maximum sequence length)	Required tap positions (in addition to input tap at position 0)
2	3	1,2
3	7	1,3
4	15	1,4
5	31	2,5
6	63	1,6
7	127	3,7
8	255	2,3,4,8

channel interference, but if the original signal spectrum is fairly uniform that of the interference will also be uniform and of a lower level than would obtain for a 'peaky' wanted-signal spectrum. Scrambling can therefore reduce potential interference problems.

In conclusion, scrambling was shown to be beneficial with d.p.c.m. signals and essential with p.c.m. signals. A length of 5 stages for each of the 6 parallel scramblers appeared to be sufficient, although (apart from the tests just described) 7 stages were normally used as there was no apparent disadvantage in doing so while it was thought to offer a greater safety margin. (An 8-stage scrambler would have caused increased error extension although this would not present any real difficulty if the error corrector was in use).

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